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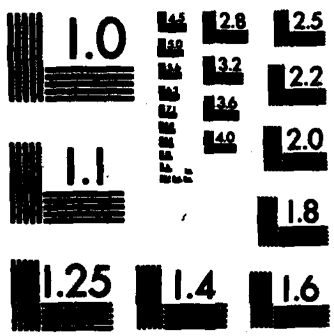
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THERMAL CONDUCTIVITY OF TERNARY AND QUATERNARY III-V COMPOUNDS

FINAL REPORT FR1

W. J. Collis
E. K. Stefanakos

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U. S. ARMY RESEARCH OFFICE

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North Carolina Agricultural and Technical
State University
Department of Electrical Engineering
Greensboro, NC 27411

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Thermal conductivity of III-V semiconductors; measurement of thermal conductivity.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This research project was directed at investigating methods of measuring the thermal conductivity of semiconducting alloys of III-V compounds (GaAℓAs, GaInAs, GaInAsP) in a thin layer format. Generally, techniques for measuring the thermal properties of bulk materials are not suited for the thin epitaxial layers which are utilized in active devices. The thermal conductivity is an important design parameter for those devices which must dissipate large amounts of power during operation.

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The proposed measurement technique utilized a conducting epitaxial alloy layer deposited upon a semi-insulating lattice-matched semiconductor substrate. The thin films were prepared by liquid phase epitaxy or current controlled liquid phase epitaxy.

In the initial measurement approach, a filamentary sample with ohmic contacts on the epitaxial layer was fabricated. A constant current was passed through this resistor and the resistance change caused by the Joule heating was monitored. This temperature-related change can, in principle, be related to the thermal properties of the epilayer and substrate. However, because the thermal conductivity of the alloy epilayer is somewhat less than that of the substrate and the epilayer/substrate thickness ratio is quite small,reasonable results could not be obtained.

Alternative sample configurations were considered, such as removing a portion of the supporting substrate to form an unsupported filamentary resistor or detecting the transient heat pulse which propagates through the structure. These were considered to require unrealistic processing or measurement techniques. The measurement problem is recognized as being somewhat analogous to the determination of a small resistance value in series with a much larger resistor. Transient measurement methods require high precision resistance measurements at a rate of at least twenty per second.

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THERMAL CONDUCTIVITY OF TERNARY AND QUATERNARY III-V COMPOUNDS

Statement of Research Problem

This research was directed at determining the thermal conductivity of epitaxially grown thin layers of III-V alloy semiconductors. The materials to be studied were GaAlAs, GaInAs and GaInAsP, grown by liquid phase epitaxy (LPE) or current-controlled liquid phase epitaxy (CCLPE). Thermal conductivity is an important parameter in injection diode lasers, high power FETs, Gunn and transferred electron devices, and concentrator solar cells in which the removal of the generated heat and thermal degradation are major problems. The lattice thermal conductivity of the III-V ternary and quaternary semiconducting alloys can be considerably larger (ten times or more) than the constituent binary compounds[1].

The measurement technique proposed utilized the transient or steady-state temperature behavior in the epilayer-substrate sample configuration. The thin film sample configuration would yield a more homogeneous single crystal material than a bulk crystallization preparation method.

Summary of Results

The initial basis for the thermal conductivity measurement was the technique described by Boyce and Chung[2]. The sample configuration consists of the thin film to be analyzed deposited upon an electrically insulating supporting substrate having known thermal properties. An electrical current is passed through the filamentary film layer and the resistance change is monitored. These data, in conjunction with a measurement of the sample temperature coefficient of resistance, can be modeled, in principle, to determine the thermal conductivity of the thin layer. Boyce and Chung demonstrated the technique with 0.2 μm silver films on 76 μm thick glass slides. The transient behavior of the resistance change or the steady-state value can be related to the thermal conductivity. This method is illustrated symbolically in Fig. 1(a).

To investigate the Boyce and Chung method, samples of nGaAs on semi-insulating GaAs substrates were prepared by LPE. Metal stripe contacts were evaporated and alloyed. Approximately one millimeter wide filamentary samples were cut with a wire saw. The test sample configuration is shown in Fig.2. The four contact method eliminates series contact resistance effects.

The Boyce and Chung method involves a measurement of the time necessary for one-half the incremental resistance change to occur. It was discovered that this transient variation in the GaAs sample resistance occurred in less than a second. The very accurate measurement of the resistance over such a brief time was not considered to be realizable, and therefore, the steady-state approach was considered.

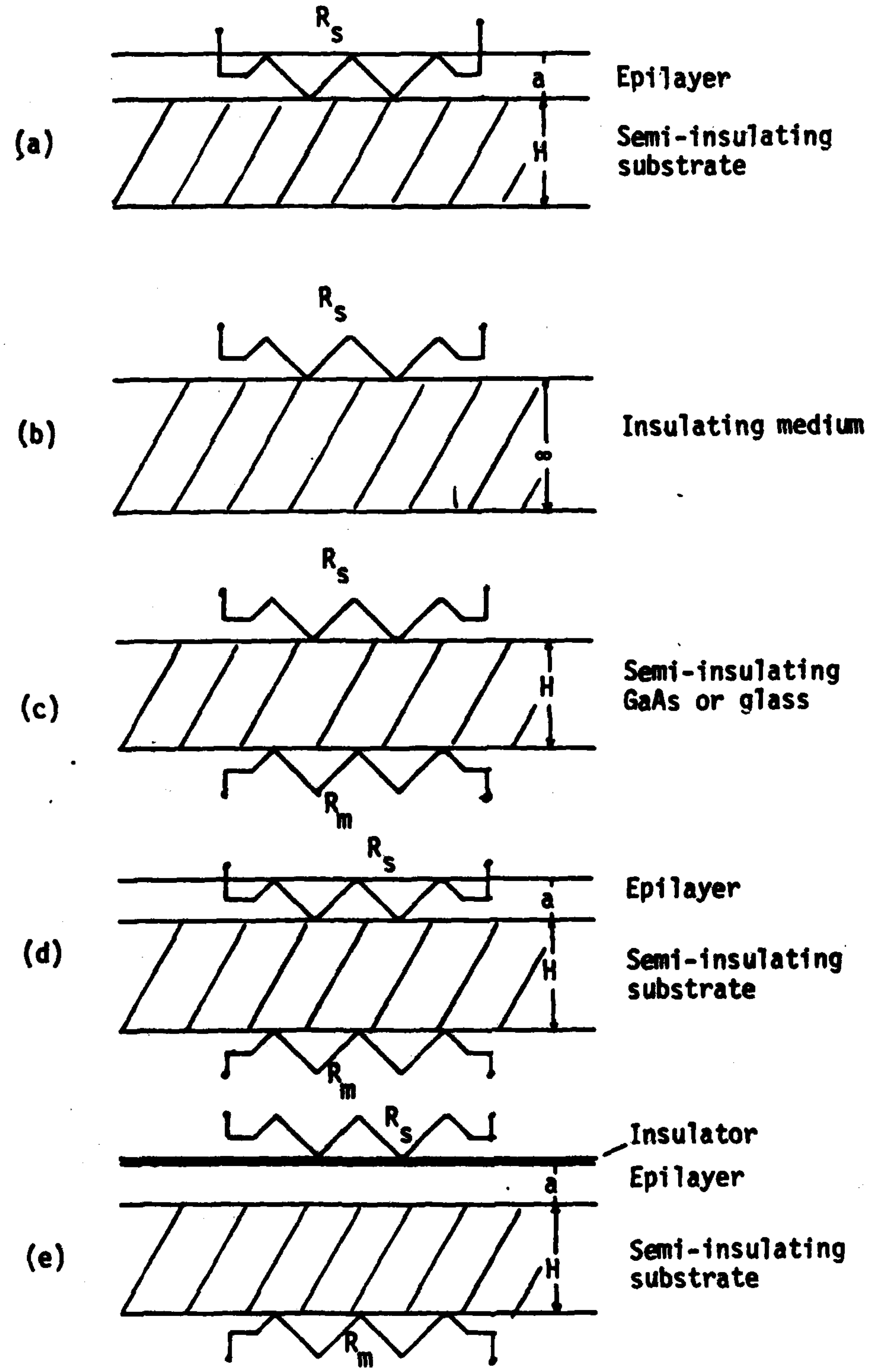

Figure 1. Various sample configurations possible for the thermal conductivity measurement of thin films. (a)Boyce and Chung configuration; (b)Gustafsson configuration; (c), (d) and (e) variations of these methods.

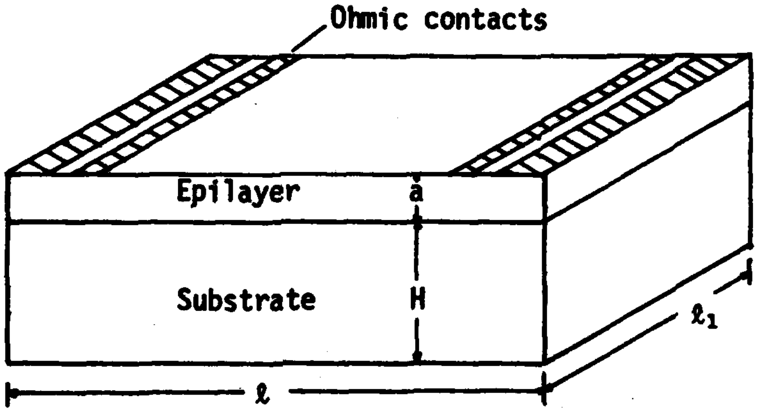

Figure 2. Sample configuration for Boyce and Chung[2] thermal conductivity measurement technique.

The steady-state temperature distribution in a sample whose ends are maintained at temperature T_0 will result in a resistance change which can be used to calculate the thermal conductivity. The equation to be iteratively solved is[2]

$$\Delta R/R_0 = (8B/\pi^2) \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2((2n+1)^2\pi^2(1+k_x a/k_s H)-B)} , \qquad (1)$$

where $B = (\partial R/\partial T)I^2 \ell/\ell_1 k_s H$, ΔR is the steady-state resistance change for a current I, R_0 is the initial sample resistance (measured with a current less than 0.1 I), $\partial R/\partial T$ is the sample temperature coefficient of resistance, ℓ = sample length, ℓ_1 = sample width, a = epilayer thickness, H = substrate thickness, k_s = substrate thermal conductivity, and k_x is the desired epilayer thermal conductivity.

Measurements to determine $\partial R/\partial T$ were performed with the sample in an inert gas environment in a variable temperature furnace. The sample container was evacuated to reduce heat losses during the measurement of ΔR.

In Eq. (1) the thermal conductivity of the epilayer appears in the $k_x a/k_s H$ term. Since $k_x \leq k_s$ and $H/a \simeq 50$, this term is quite small, and thus extreme accuracy is required in the measurement of the other parameters in the equation. Frequently, the data would yield an iterative solution for k_x which was outside the range of possible values ($0 \leq k_x \leq k_s$). Although the proposed investigation was to include the ternary and quaternary alloys, preliminary samples of GaAs epilayers and metal films on glass substrates were used to evaluate the measurement technique. The GaAs samples yielded the unsatisfactory results indicated above. Silver films on glass gave somewhat similar results to those of Boyce and Chung. But the aluminum films on glass yielded k_x values more than two times that expected for aluminum. In all of these samples the thickness of the thin film and the thermal conductivity of the substrate, k_s, are parameters which may involve considerable error. (The thicknesses were determined with an optical microscope or stylus surface profiler, and the k_s values were obtained from the literature.)

Consideration was given to reducing the a/H ratio in Eq. (1) by removing a portion of the substrate. This led to a very fragile sample which could not be satisfactorily mounted in the measurement system. An alternative method was to completely remove the substrate by selective chemical etching to define the filamentary sample. This would require an appropriate thermal model with longitudinal heat conduction in the film to the heat sinked ends. Such selective chemical etching may be possible in the heterostructure samples (e.g., GaAlAs-GaAs, GaInAs-InP, and GaInAsP-InP)[3-8]. The etching of the pattern through the substrate resulted in considerable undercutting of the mask (sputtered SiO_2). Again, this type of structure was considered too fragile to pursue because the filamentary epilayer would be supported only at the ends.

An alternative method of reducing the a/H ratio would be increasing the epilayer thickness. However, the limited melt size in the available LPE or CCLPE systems would lead to a compositional variation in the ternary or quaternary layers.

The uniqueness of the Boyce and Chung measurement technique is that the material to be tested is used as the heat source. A somewhat similar approach, utilizing an auxiliary heat source, is described by Gustafsson, et al.[9,10] The approach is symbolically illustrated in Fig. 1(b). A thin plane strip heater is embedded in an infinite solid or liquid, or deposited upon a semi-infinite solid. A current source heats the strip and the transient resistance change is measured. The data analysis yields the thermal conductivity and thermal diffusivity of the surrounding or adjacent material. This technique was investigated as a means of achieving the goals of this research.

The Gustafsson measurement method assumes an initial isothermal system. When power is applied to the heater strip, the heat is conducted away into the surrounding medium. The initial resistance-time response, the resistance temperature coefficient, the input power, and the heater dimensions are necessary for the solution. Since the semiconductor samples are of finite thickness ($\sim$250-500 μm), an experiment was performed to determine if such samples would adequately meet the boundary conditions during a short interval. Samples of semi-insulating GaAs and glass were fabricated with Cr-Al film resistors approximately aligned on the opposite surfaces. Thus, one resistor pattern served as the heat source, and the other pattern was used to detect the temperature rise at the opposite surface (see Fig. 1(c)). In both samples the temperature transient was observed within a fraction of a second. Measurements were performed with an internally triggered HP3455A system voltmeter and stored in a HP1000 minicomputer. The sampling rate was approximately 10 readings/second. While this technique could be improved by employing thicker samples and an externally timed measurement system, it may not be directly applicable to the existing measurement problem. Since most of the epilayers are electrically conducting, an insulating layer would have to be deposited between the epilayer and the metal film heater.

It may be possible that a careful comparison of the response of the heater strip resistance and the opposite surface resistor will yield an effective thermal conductivity of the composite sample (see Figs. 1(d) or 1(e)). While not yielding the thermal conductivity of the epilayer, the effective thermal conductivity of the composite structure may actually be of more interest in device applications. However, this technique would require a precise alignment of the resistor patterns, and rapid, highly accurate resistance measurements. Thus, the work on this research project is concluded with the recognition that detecting the thermal properties of a thin layer in contact with a similar bulk material requires processing or measurements beyond the existing capabilities of this laboratory.

An extension in the grant period was requested so that samples of polycrystalline III-V alloys on sapphire and quartz substrates could be fabricated by chemical vapor deposition at North Carolina State University. Various technical problems associated with the growth system prevented the samples from being delivered for analysis by the Boyce and Chung method.

Appendix A contains a list of the scientific personnel participating in this project. In Appendix B the abstracts of the two MSEE theses completed during this research are presented. There were no scientific publications as a result of this research.

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Appendix A: Participating Scientific Personnel

Faculty

Dr. A. Abul-Fadl
Dr. W. J. Collis
Dr. A. Haque
Dr. S. Iyer
Dr. J. W. McPherson
Dr. E. K. Stefanakos

Graduate Students

Mr. R. Banikazemi
Mr. L. Bhangu
Mr. B. Chilukuri
Mr. M. Denduluri
Mr. M. Heidary
Mr. S. Rastani
Mr. A. Ravindra
Mr. Y. Taghipoor-Tabrizi

Appendix B: Abstracts of MSEE theses

1. Thermal Conductivity Measurements in Thin GaAs Layers, by Reza Banikazemi, (1981).

2. A Study of Techniques for Thermal Conductivity Measurements of Epitaxial Semiconductor Layers, by Alluri Ravindra, (1983).

THERMAL CONDUCTIVITY MEASUREMENTS IN THIN GaAs LAYERS

By Reza Banikazemi

(W. J. Collis, Advisor)

(1981)

The thermal conductivity measurement of liquid phase epitaxially grown layers of GaAs is presented. For power dissipating devices such as photovoltaic solar cells (used in concentrator-type applications), high frequency high power FET's, diodes and transferred electron devices, it is useful to know the value of the thermal conductivity to assist in device and circuit design. A theoretical discussion of thermal conductivity in semiconductor materials is also presented.

This proposed technique uses thin layers GaAs grown upon semi-insulating GaAs substrates. A dc electrical current is allowed to pass along the epilayer, thus creating a temperature gradient. The thermal conductivity is deduced from the measured change in resistance. The experimental results indicate that further analysis of the technique is necessary to achieve reasonable results.

The experimental work was performed in the Rockwell Solid State Electronics Laboratory at North Carolina A&T State University.

A STUDY OF TECHNIQUES FOR THERMAL CONDUCTIVITY MEASUREMENTS OF EPITAXIAL SEMICONDUCTOR LAYERS

By Alluri Ravindra

(Dr. Ward J. Collis, Advisor)

(1983)

Knowledge of the thermal conductivity of semiconductors forms an important part in the design of power dissipating devices and thermoelectric devices. Various techniques for thermal conductivity measurement of epitaxial semiconductor layers are presented. The techniques include the Boyce and Chung approach and the Gustaffson approach.

In the Boyce and Chung approach, a DC electrical current is allowed to pass along the epilayer, thus creating a temperature distribution. The thermal conductivity is deduced from the measured change in electrical resistance. The deviations of the experimental results from the already established values are explained to some extent. Also, the sensitivities of the thermal conductivity values due to variations in the various parametric values are presented.

Similar to the Boyce and Chung method, in the Gustaffson approach a constant current is also applied to a metal strip. Unlike the Boyce and Chung method, here the transient data of the resistance change is analyzed to obtain the thermal transport properties. The difficulties encountered in this method are also presented.

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